

Towards B_s Mixing With CDFII

Ivan K. Furić, M.I.T.

- Tevatron & CDFII
- B mixing measurement setup
- $\text{Br}(B_s^0 \rightarrow D_s^- \pi^+)$
- Prospects

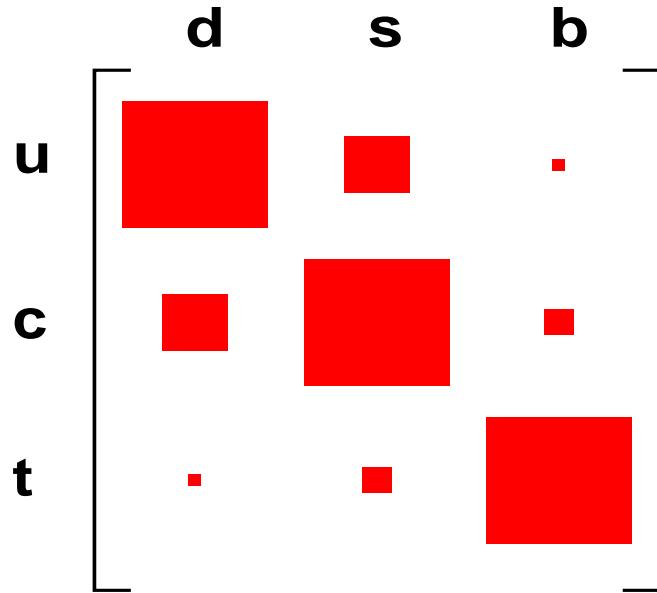
University of California - San Diego Seminar, Dec 1, 2003

Introduction/Roadmap

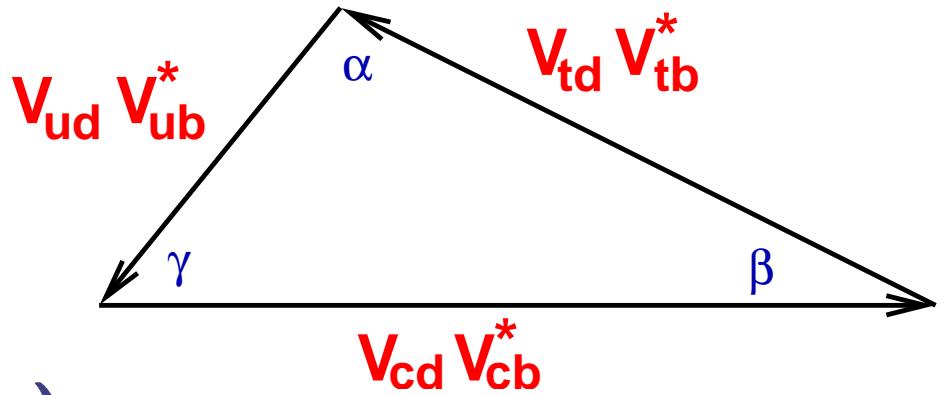
- measurements of B^0 and B_s mixing contribute to our understanding of weak interactions
- combined with measurements from B factories, they test the SM

- flagship measurement for CDF II B program
- overview measurement technique and issues
- focus on the measurement of $Br(B_s \rightarrow D_s^- \pi^+)$
- determines size and properties of our main sample
- use results of this analysis to project B_s mixing reach

Weak Interactions in the SM

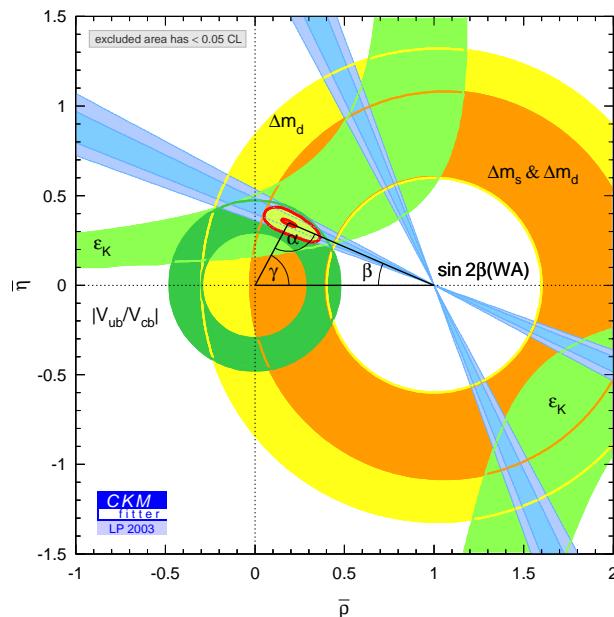
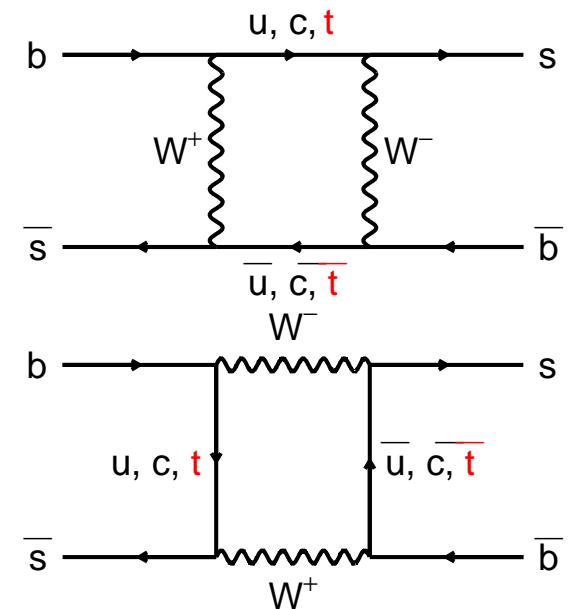


- CKM matrix: W^\pm boson couplings to quarks
- area $\sim |V_{ij}|$
- interaction strength $\sim |V_{ij}|^2$
- unitary matrix: $VV^\dagger = 1$
- unitary triangle
- 1 observable phase (\sim area, \sim CP violation)
.. how does B_s mixing fit into this?



B Mixing and the Unitarity Triangle

- both B_d and B_s mesons mix
- ratio of mixing frequencies:
measures one side of the unitarity triangle ($|V_{td}/V_{ts}|$)
- indir. meas: $\Delta m_s \leq 24 \text{ ps}^{-1}$
- overconstrain → **test SM**



Input for unitarity triangle fits:

- CP violation in K, B system
- $B \rightarrow \pi l \nu X$ vs $B \rightarrow D l \nu X$
- B_d, B_s meson mixing
- direct measurements of α, γ

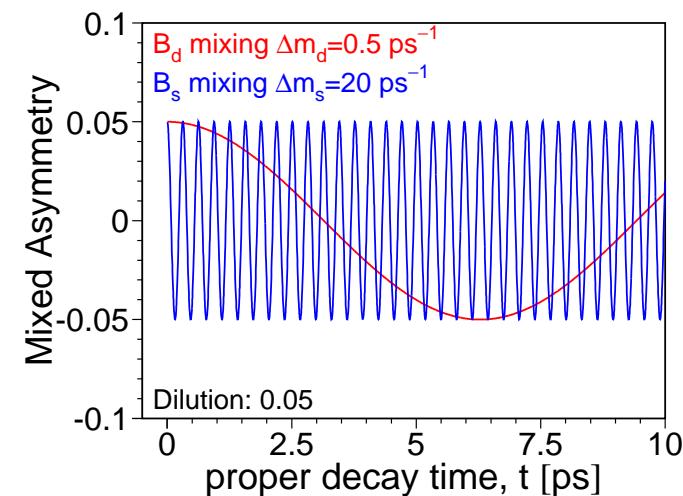
$B_{(s)}$ Mixing Measurement Ingredients

Per B meson decay,

- determine decay flavor [use **flavor specific** states]
- identify B meson production flavor [**flavor tagging**]
- measure B proper decay time [***ct* resolution**]

Time-dependant asymmetry:

$$\begin{aligned} A_{mix}(t) &= \frac{N_{unmix}^{obs}(t) - N_{mix}^{obs}(t)}{N_{unmix}^{obs}(t) + N_{mix}^{obs}(t)} \\ &= (2p - 1) \cdot \cos(\Delta m \cdot t) \end{aligned}$$



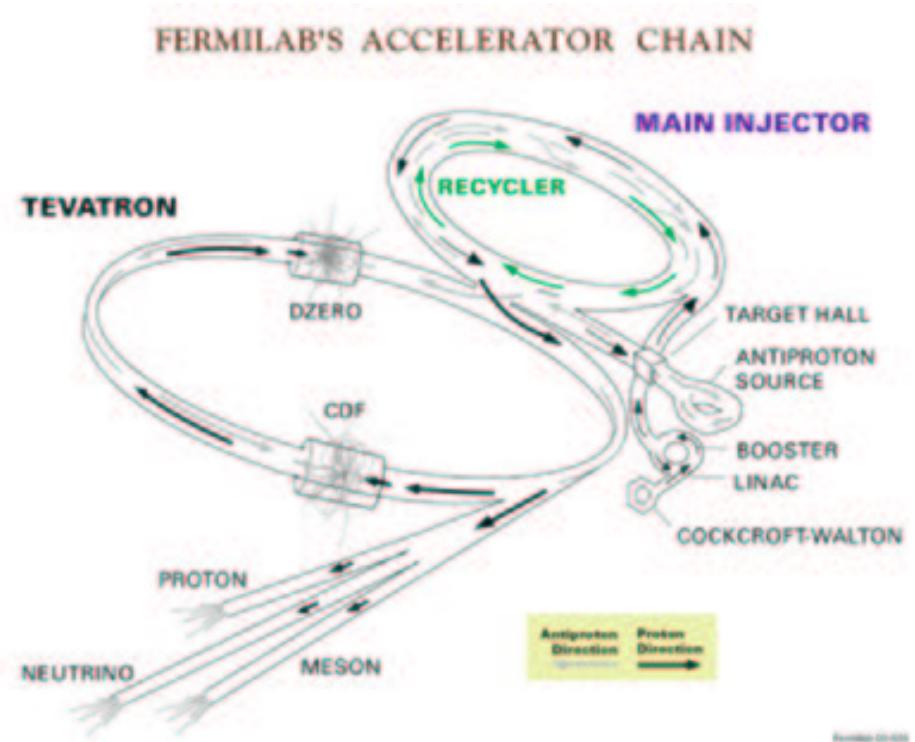
Oscillation amplitude: $2p - 1 = D$ [**dilution**]

$$\text{Significance} = \sqrt{\frac{S\epsilon D^2}{2}} e^{\frac{-(\Delta m)\sigma(c\tau)}{2}} \sqrt{\frac{S}{S+B}}$$

Apparatus: Tevatron

Main Injector

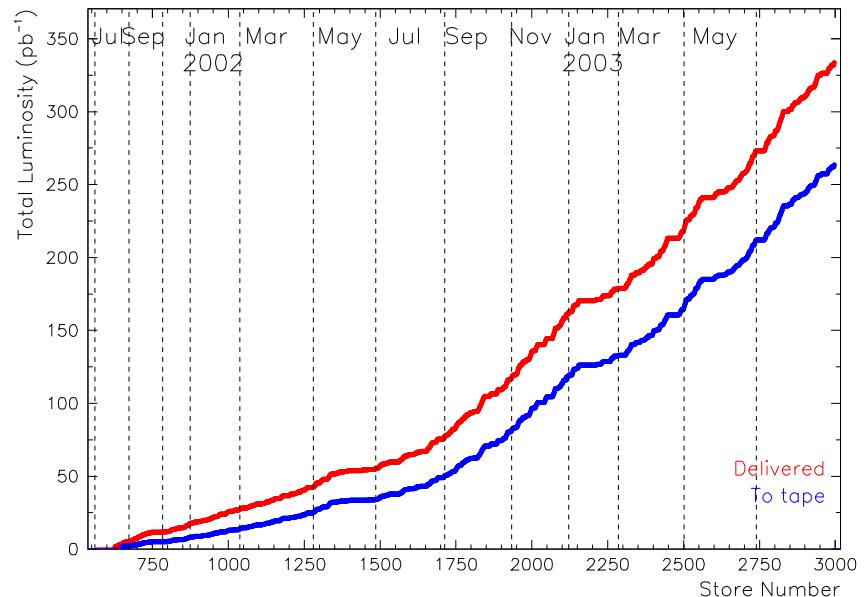
- New injection stage for Tevatron
- Ability to accelerate and deliver higher intensity of protons
- More efficient \bar{p} transfer
- \bar{p} recycler (in progress)
- Higher Collision rate: 396ns (36x36 bunches)
⇒ 5-10 Higher Luminosity than Run I
- Higher C.M. Energy:
Run I: 1.8 TeV → Run II 1.96 TeV



Tevatron Luminosity

Tevatron Performance

- Below expectation but improving
 - Record luminosity: $4.8 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$
 - Now consistently $4 - 7 \text{ pb}^{-1}$ per week



At CDF:

- 330 pb⁻¹ delivered, 260 pb⁻¹ recorded
- $\sim 200 \text{ pb}^{-1}$ all important systems on
- analyses shown use 12 – 120 pb⁻¹
(depending on when they were done)

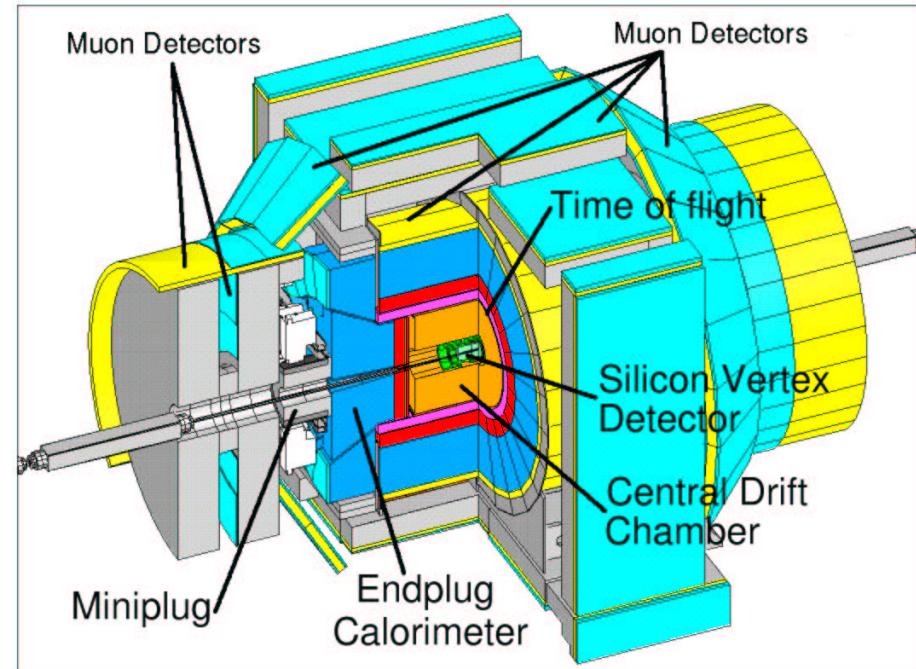
Apparatus: The CDF II Detector

Inherited from Run I:

- Central Calor. ($|\eta| < 1$)
- Solenoid (1.4 T)

Partially new:

- Muon System
(extended to $|\eta| < 2$)



Completely new:

- 3D Silicon Tracker ($|\eta| < 2$)
- Faster Drift Chamber
- Plug and Forward Calorimeters, Time Of Flight
- Trigger System (trigger on displaced vertices)

B Mixing in $p\bar{p}$ collisions

- produce all B species: $B^0, B^+, B_s, B_c, \Lambda_b$
- huge B production cross section: $\sim 100 \mu b$
($3 - 5 \mu b$ “reconstructable”)
at $4 \cdot 10^{31} \text{cm}^{-2}\text{s}^{-1}$, 150 Hz reconstructable B's
- large inelastic ($\sigma \times 1000$) background
⇒ triggering very important
- B's boosted in the transverse plane (ct measurement)
- less production flavor information than at e^+e^-
- B^0 mixing routinely done in Run I

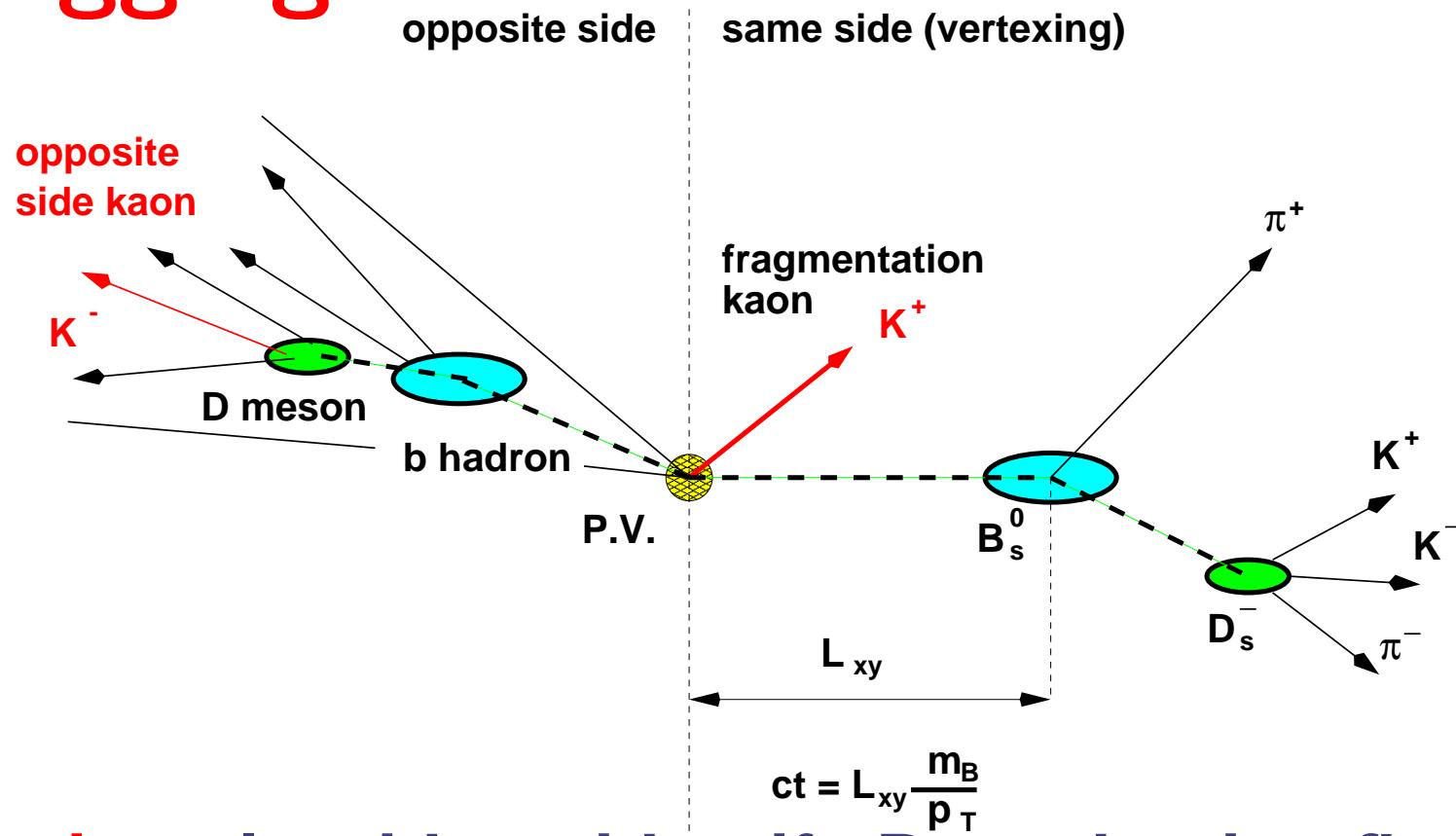
Reminder: Measurement Ingredients

Per B meson decay,

- determine decay flavor [use **flavor specific states**]
 - identify B meson production flavor [**flavor tagging**]
 - measure B proper decay time [***ct* resolution**]
-

Focus: flavor tagging techniques

Tagging The Production Flavor

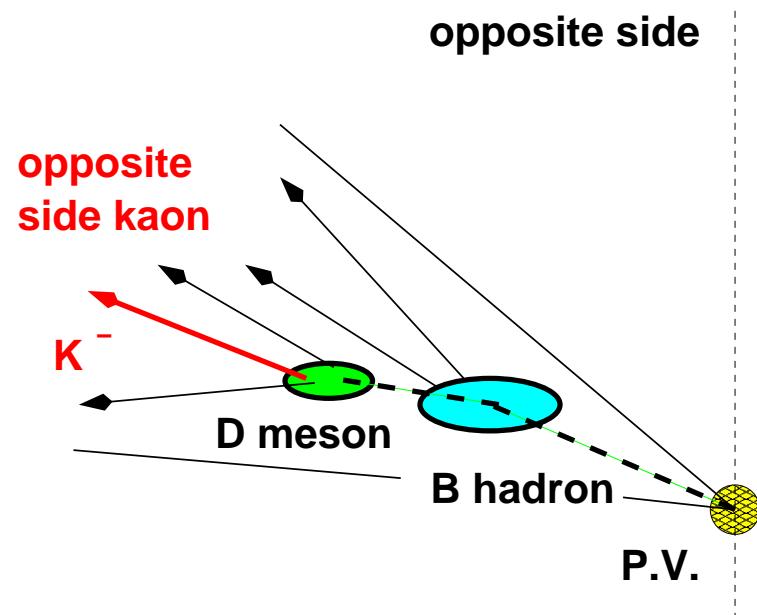


$$ct = L_{xy} \frac{m_B}{p_T}$$

- Tagging algorithms identify B production flavor
- **Opposite Side Tagging**: B 's produced in pairs, identify the flavor of the opposite B meson
- **Same Side Tagging**: hadronization π/K charge is correlated to B_d/B_s production flavor

Tagging: Opposite Side Tagging

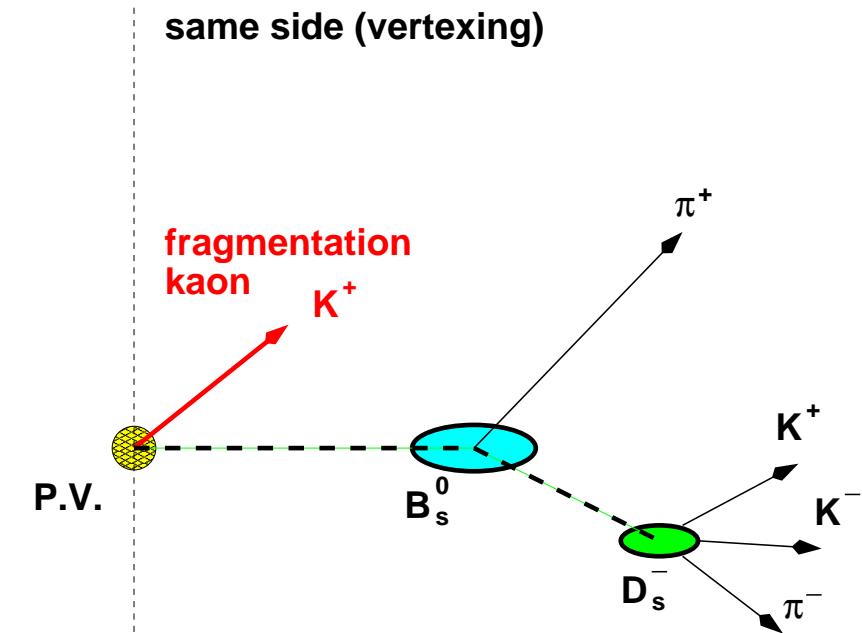
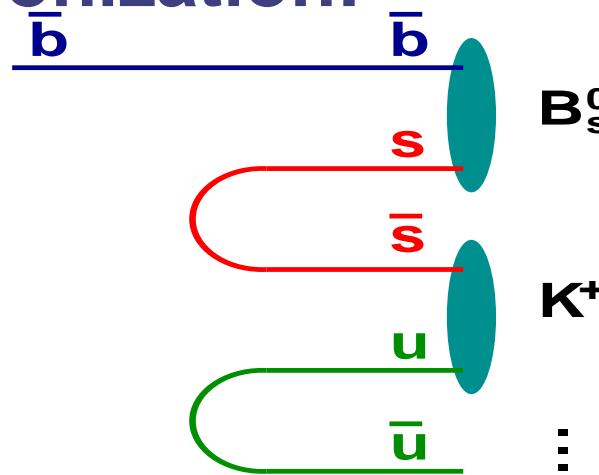
- **Lepton Tagging:** find lepton from $B \rightarrow D l \nu X$
- **Jet Charge Tagging:** momentum-weighted sum of track charge in B jet (+ displacement)
- **Kaon Tagging:** assume $b \rightarrow c \rightarrow s$ decay, find kaon in B jet



- Difficulties with OST:
- 20-40% opposite side B's inside detector acceptance
- B^0, B_s^0 mix \rightarrow production flavor information lost

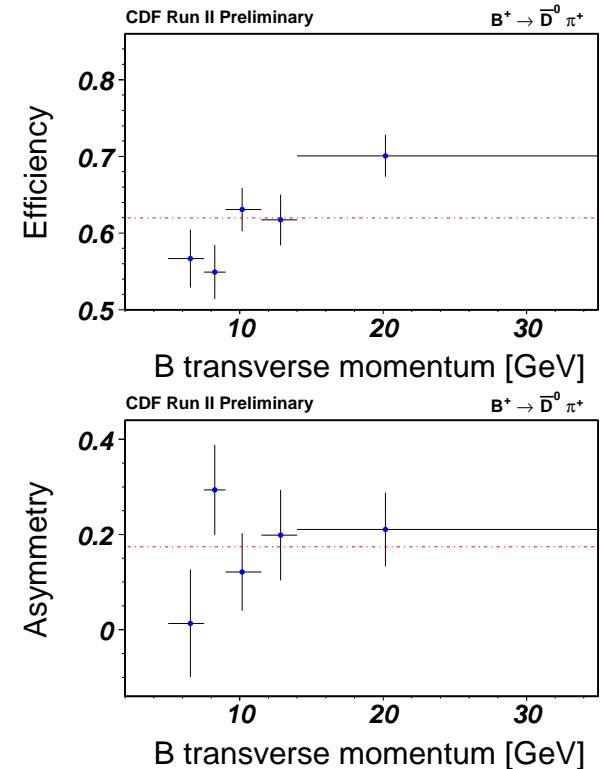
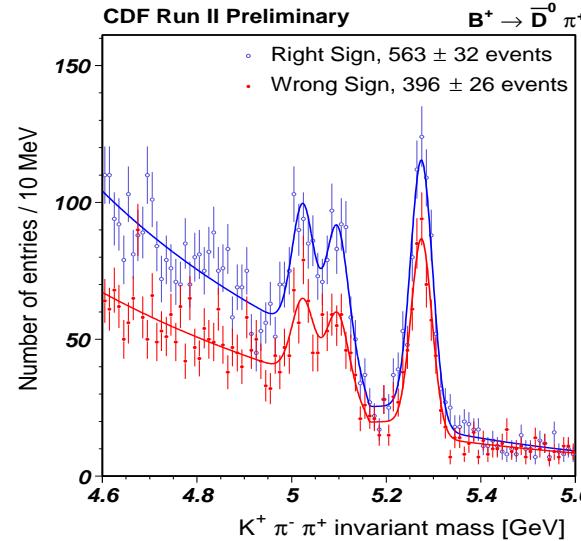
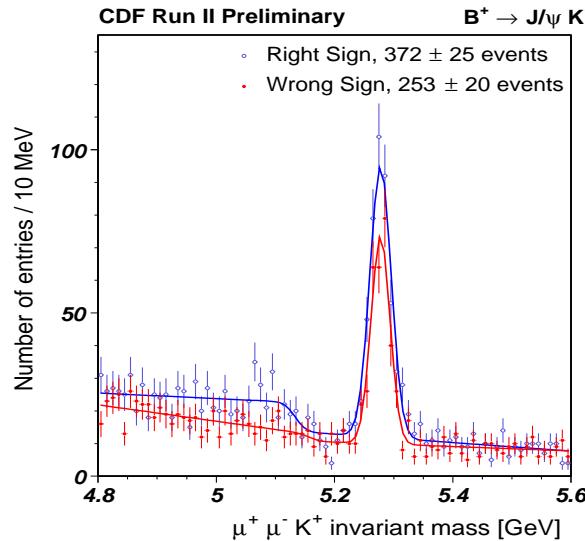
Tagging: Same Side Tagging

Exploit signature of B_s hadronization:



- 80% of tracks in event are pions [kaons $\sim 10\%$]
- fragmentation tracks are soft \rightarrow TOF particle ID
- Run I B^0 mixing using track SST
- expect improvement using TOF particle ID
- combined (OST + SST) tagging power: $\epsilon D^2 \sim 5\%$

Tagging Efforts in Run II



- fully reconstructed B^+ decays
- measure efficiency and dilution
- example: same side pion tag
- $B^+ \rightarrow J/\psi K^+$: $\epsilon D^2 = 2.4 \pm 1.2(stat)\%$
- $B^+ \rightarrow \bar{D}^0 \pi^+$: $\epsilon D^2 = 1.9 \pm 0.9(stat)\%$
- Run I $J/\psi K^*$: $\epsilon D^2 = 1.8 \pm 0.4(stat)\%$

Reminder: Measurement Ingredients

Per B meson decay,

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 - identify B meson production flavor [**flavor tagging**]
 - measure B proper decay time [**ct resolution**]
-

Focus: ct Resolution

- importance of ct resolution
- triggering on fully hadronic B (and charm) decays
- digression: D meson mass difference measurement
- rate of fully hadronic B_s decays
- \Rightarrow mixing reach projection

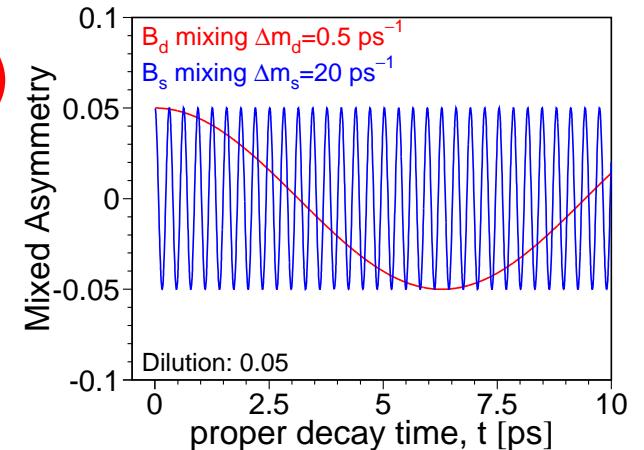
Precise ct Measurements

- rapid oscillations:

$\Delta m_s \geq 13.1 \text{ ps}^{-1}$ (90%CL, PDG)
(indir. meas: $\leq 24 \text{ ps}^{-1}$)

- very good ct resolution needed:

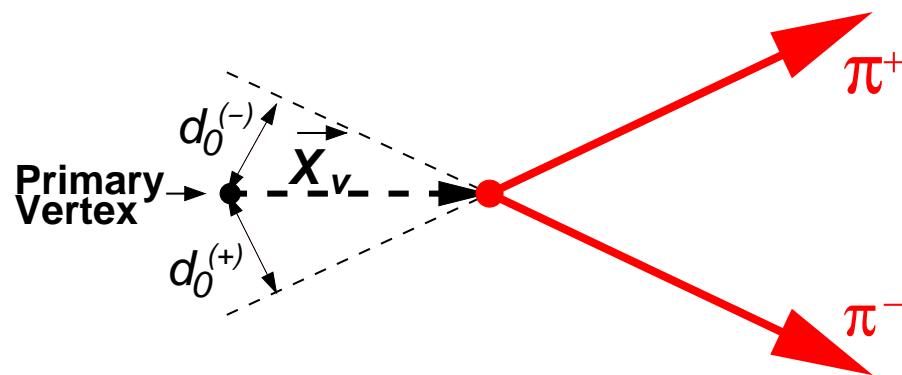
$$\sigma_{ct} = \left(\frac{\sigma_L}{\gamma\beta} \right) \oplus \left(\frac{\sigma_{\gamma\beta}}{\gamma\beta} \right) \cdot ct$$



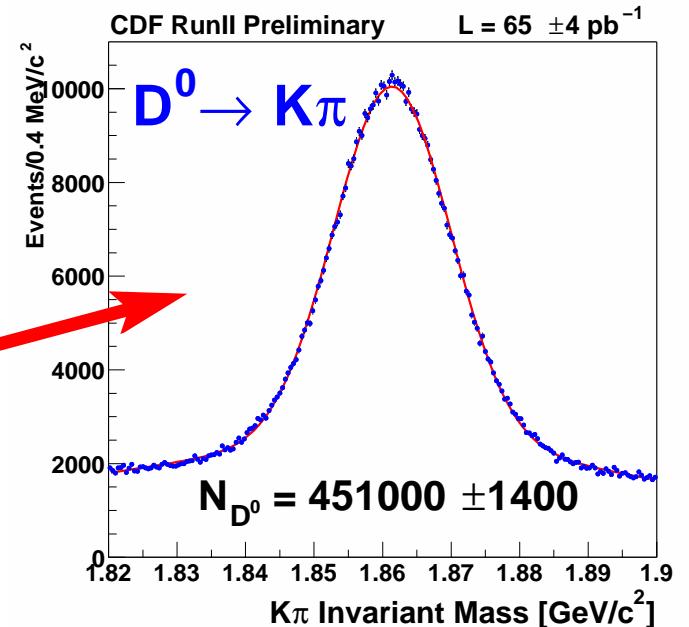
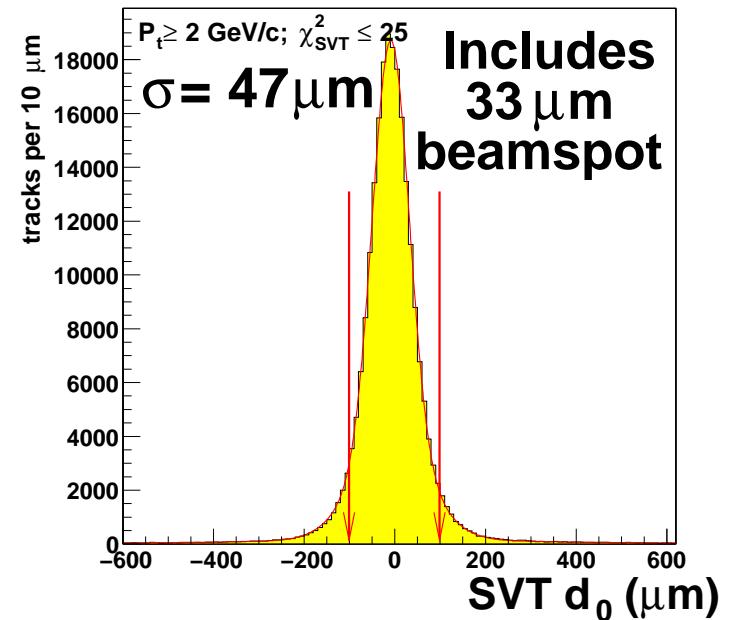
- semileptonic decays: B momentum error $\sim 15\%$
- hadronic decay ($B_s \rightarrow D_s\pi$) negligible ($\sim 0.1\%$)
- using base RunII silicon : 60 fs $\Delta m_s \sim 17 \text{ ps}^{-1}$
- layer of Si on beampipe: 45 fs $\Delta m_s \sim 22 \text{ ps}^{-1}$
- Problem: how do we trigger on these decays?

Triggering on displaced tracks

- trigger $B \rightarrow \pi\pi, B_s \rightarrow D_s\pi$
- challenge: read out SVX and track at 10's of kHz \rightarrow SVT

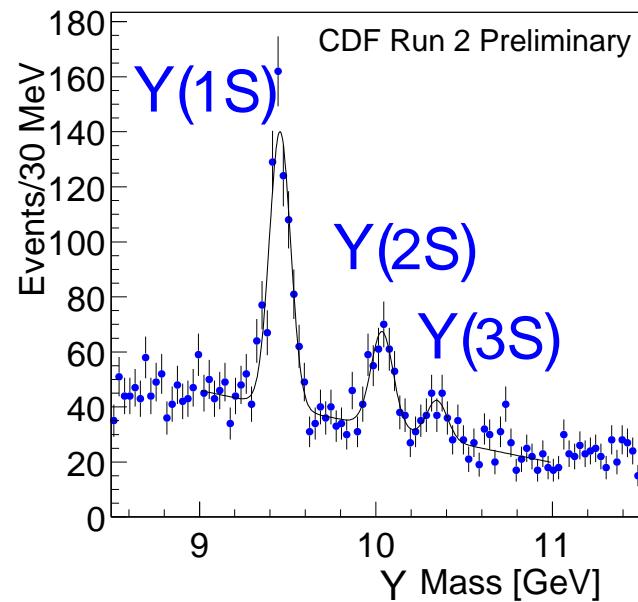
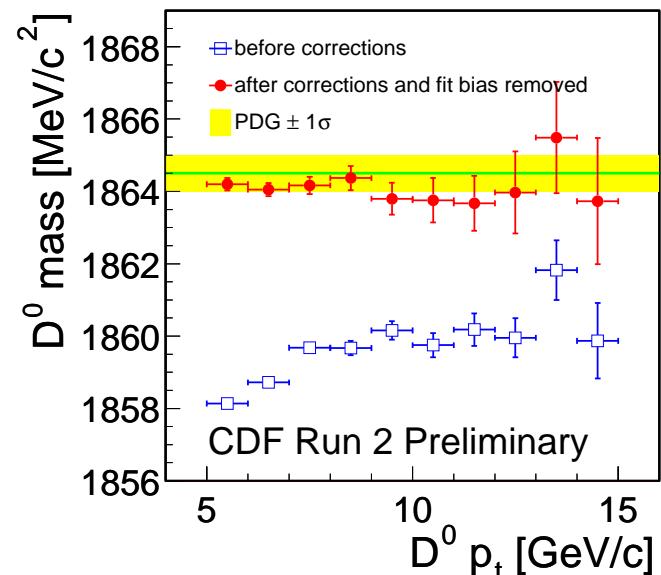
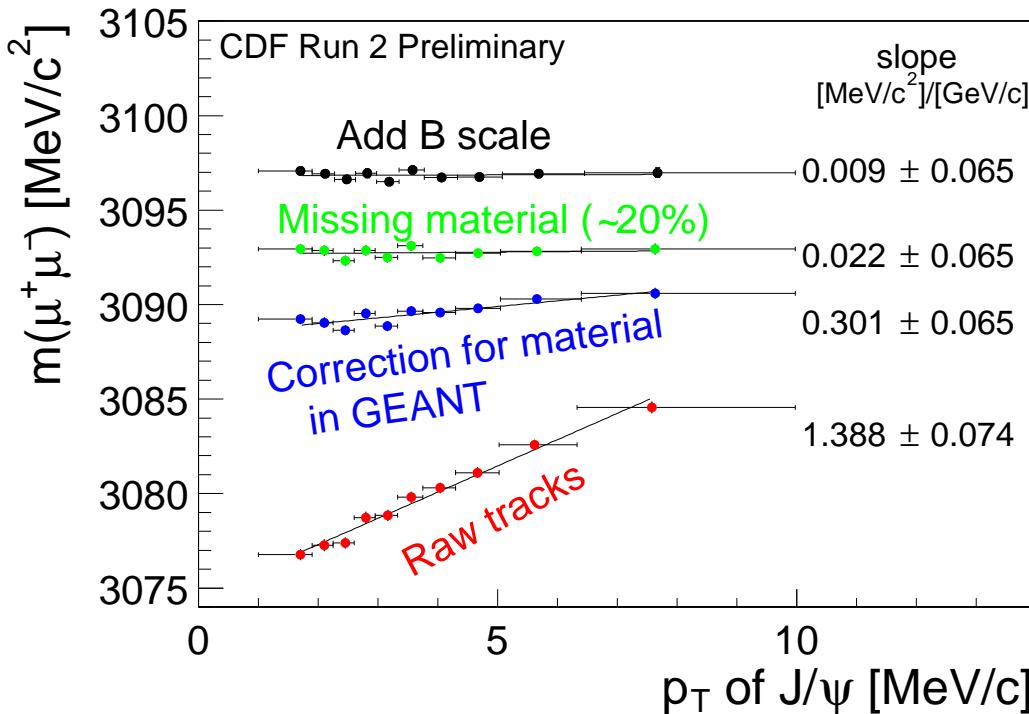


- trigger on 2 displaced tracks
($p_T > 2 \text{ GeV}/c, 120 \mu\text{m} < |d_0| < 1 \text{ mm}$)
- huge charm samples gathered
- with small int. luminosity,
competitive charm analyses

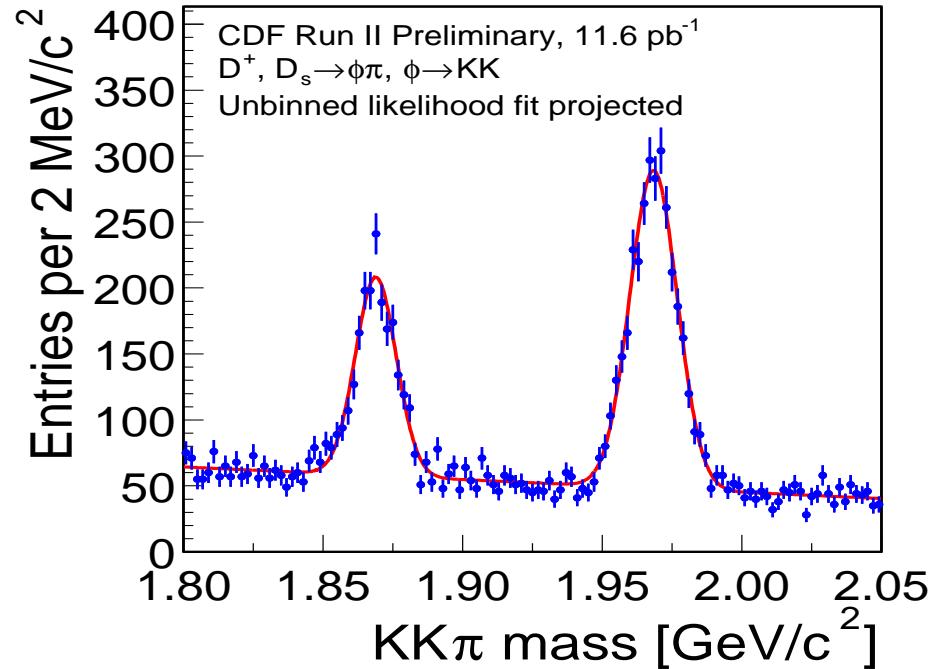


Momentum Scale Calibration

- study J/ψ 's to calibrate:
 - energy loss in detector
 - magnetic field value
- crosscheck with other decays



D Meson Mass Difference



$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(\text{stat}) \pm 0.21(\text{syst}) \text{ MeV}/c^2$$

PRD 68 (2003) 072004 - First Tevatron Run II publication

- PDG '02: $99.2 \pm 0.5 \text{ MeV}/c^2$
- CLEO2 (1998): $99.5 \pm 0.6 \pm 0.3 \text{ MeV}/c^2$
- BaBar (2002): $98.4 \pm 0.1 \pm 0.3 \text{ MeV}/c^2$

Reminder: Measurement Ingredients

Per B meson decay,

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 - measure B proper decay time [***ct* resolution**]
-

Focus: Rate of fully reconstructed hadronic B_s decays

- use as input for mixing reach projection

Fully Hadronic B_s decays

- good for B_s mixing because of good ct resolution
- $B_s^0 \rightarrow D_s^- \pi^+$ “golden mode”
 - fully hadronic, flavor specific
 - few tracks \rightarrow “easy” to trigger, reconstruct
 - $D_s^- \rightarrow \phi^0 \pi^-$, $\phi^0 \rightarrow KK$ narrow resonance
(cut on KK invariant mass \rightarrow good S/N)
- first observed at LEP
- branching fraction? (PDG: <13%, 95% CL)
(determines number of B_s available for mixing)
- initially assumed $\sim Br(B^0 \rightarrow D^- \pi^+)$
- background composition? S/B ?
- answers: branching fraction measurement

Rate of B_s vs B^0

- want to understand rate of $B_s \rightarrow D_s^- \pi^+$
 - compare to similar decay $B^0 \rightarrow D^- \pi^+$
 - count how many B_s vs B^0 are reconstructed
 - what is different?
-
- rate of B_s production different from B^0
 - f_s/f_d probability for b to hadronize as B_s/B^0
-
- final state $D_s \rightarrow \phi\pi$ vs $D^- \rightarrow K^+\pi^-\pi^-$
 - account for by using PDG ratio of BR's
-
- kinematics slightly different \rightarrow efficiency?
 - $\epsilon = \epsilon(\text{acc}) \cdot \epsilon(\text{det}) \cdot \epsilon(\text{trig}) \cdot \epsilon(\text{rec})$
 - will need to consult Monte Carlo simulation for this

$Br(B_s^0 \rightarrow D_s^- \pi^+)$ Measurement: We measure the ratio of branching fractions:

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \rightarrow D_s \pi)}{Br(B^0 \rightarrow D^- \pi)} = \frac{N(B_s^0)}{N(B^0)} \cdot \frac{\epsilon(B^0)}{\epsilon(B_s^0)} \cdot \frac{Br(D^+ \rightarrow K\pi\pi)}{Br(D_s \rightarrow \phi\pi, \dots)}$$

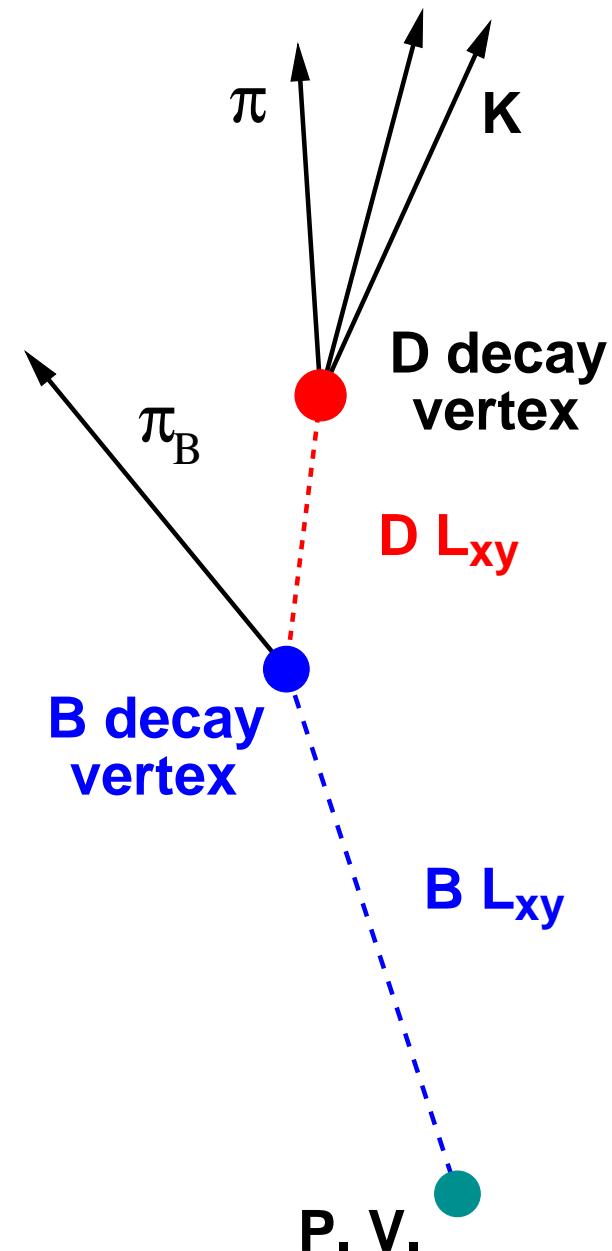
- control sample: $B^+ \rightarrow \overline{D^0}\pi^+$ and corresponding BR relative to $B^0 \rightarrow D^- \pi^+$
- $N(B_s^0)$, $N(B^+)$, $N(B^0)$ obtained from fits to data
- $\epsilon(B^0) / \epsilon(B_s^0)$, $\epsilon(B^0) / \epsilon(B^+)$ from realistic MC
- $BR(D^- / D_s^- / D^0)$ are taken from PDG

Key issues:

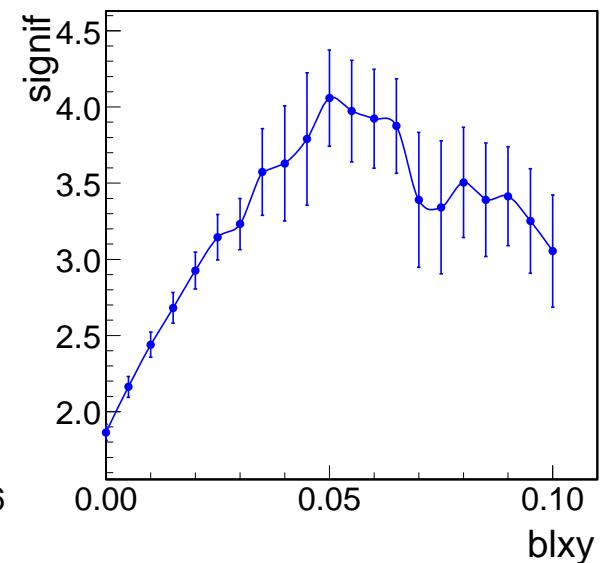
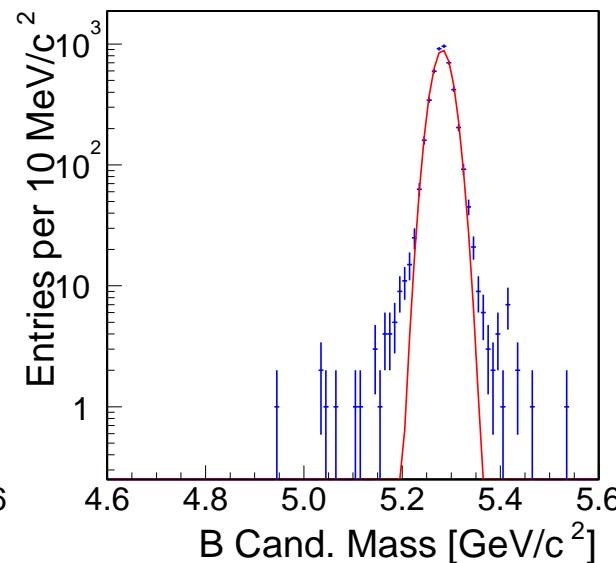
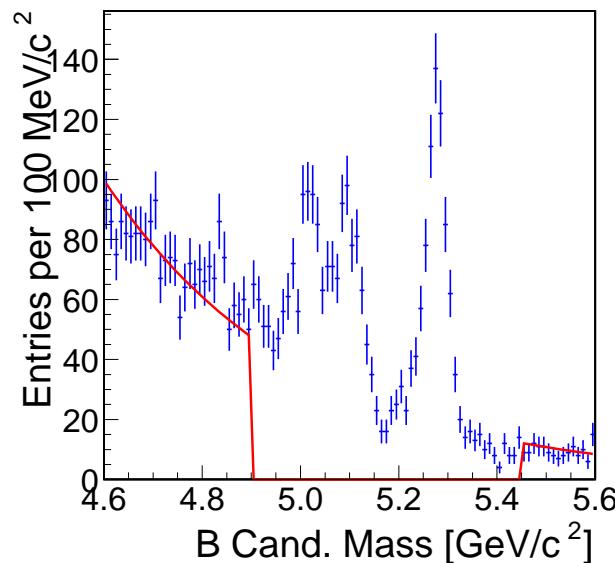
- reconstruction of B mesons with good S/B
- robust and correct extraction of $N(B)$
- realistic trigger and analysis simulation

Typical B meson selection cuts:

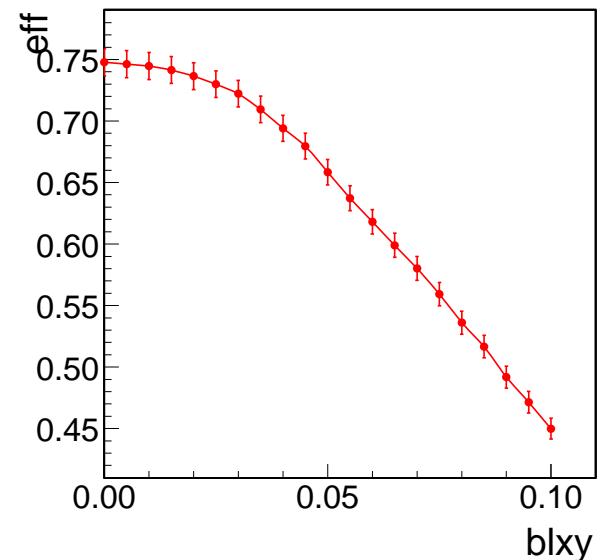
- $\chi^2_{r,\varphi}(D) < 14$
- $\chi^2_{r,\varphi}(B) < 15$
- $p_T(D) > 3.5 \text{ GeV}/c$
- $p_T(B) > 5.5 \text{ GeV}/c$
- $L_{xy}(B) > 400\mu\text{m}$
- $L_{xy}(B \rightarrow D) > -150\mu\text{m}$
- $\Delta R(D, \pi_B) < 1.5$
- $p_T(\pi_B) > 1.6 \text{ GeV}/c$
- $|d_0(B)| < 80\mu\text{m}$
- **ϕ^0 mass cut for B_s^0**
 $(1010 \text{ MeV}/c^2 < m(\phi^0) < 1028 \text{ MeV}/c^2)$



B Meson Selection Optimization:

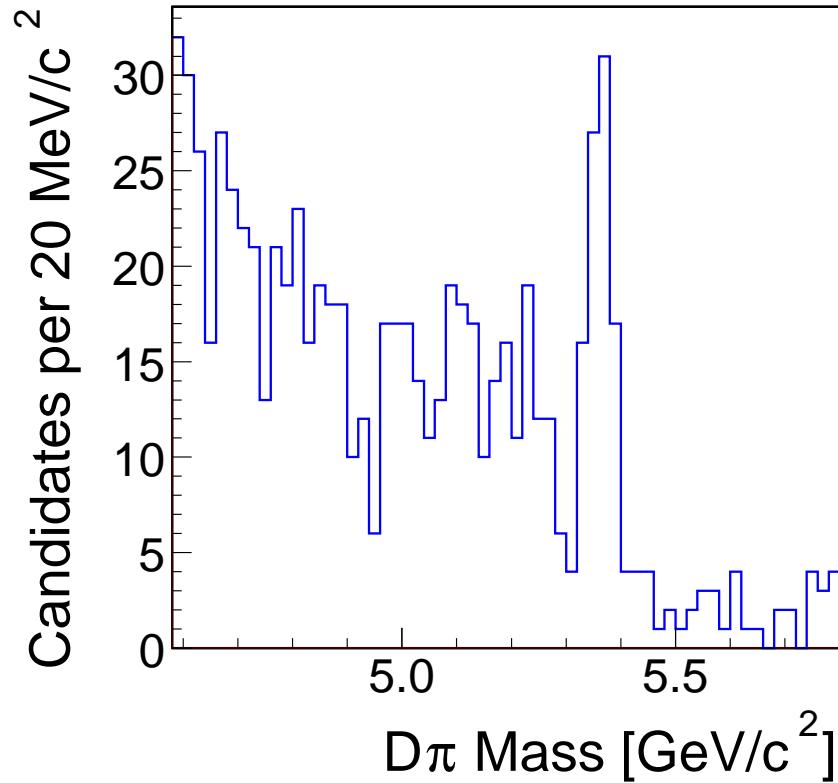


- optimize $S/\sqrt{S + B}$
- keep efficiency high
- background estimate from data
- signal estimate from scaled MC
- similar cuts from both studies

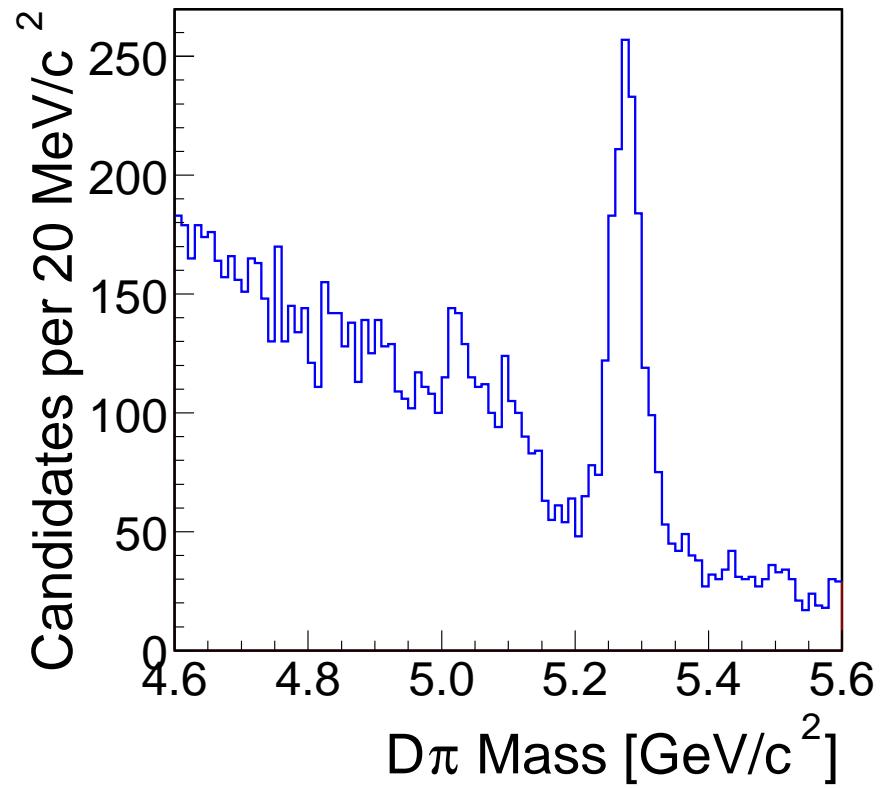


B Meson Mass Spectra:

$$B_s^0 \rightarrow D_s^- \pi^+$$

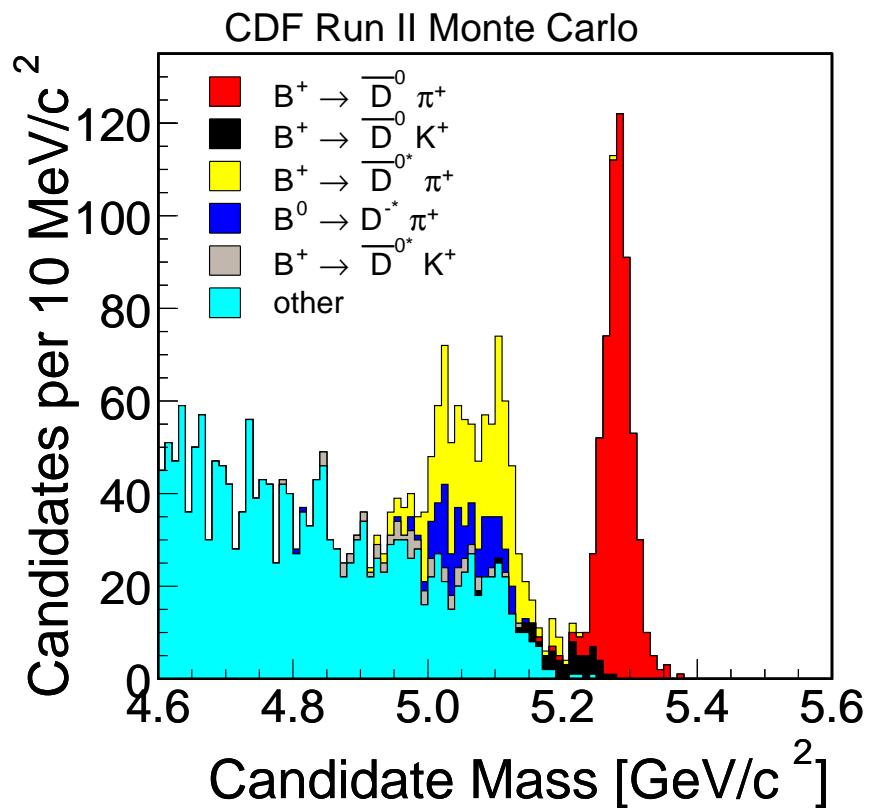
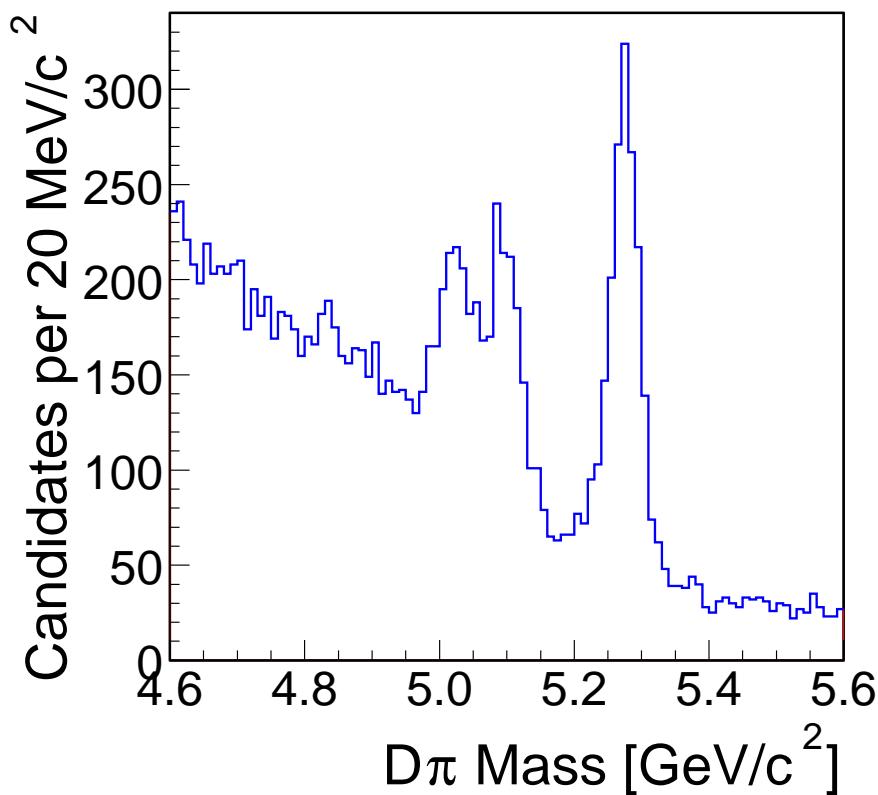


$$B^0 \rightarrow D^- \pi^+$$



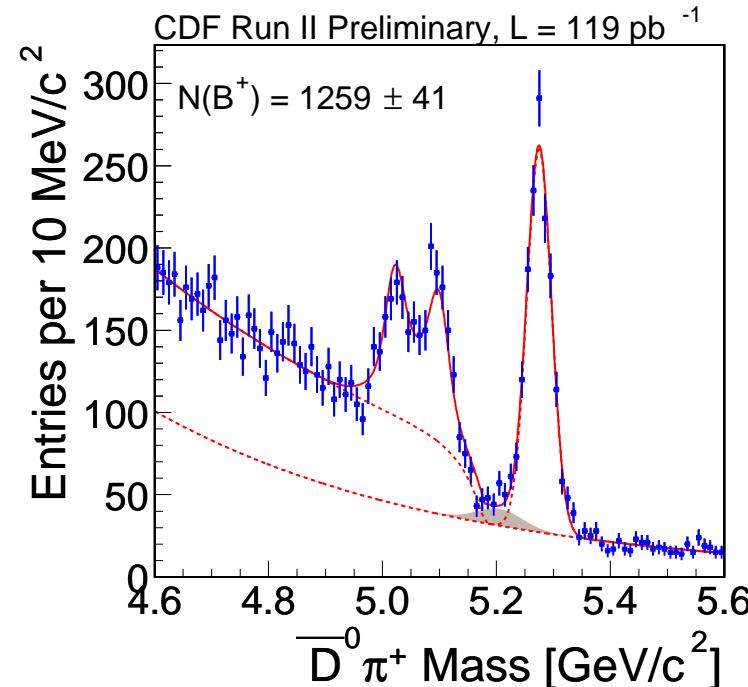
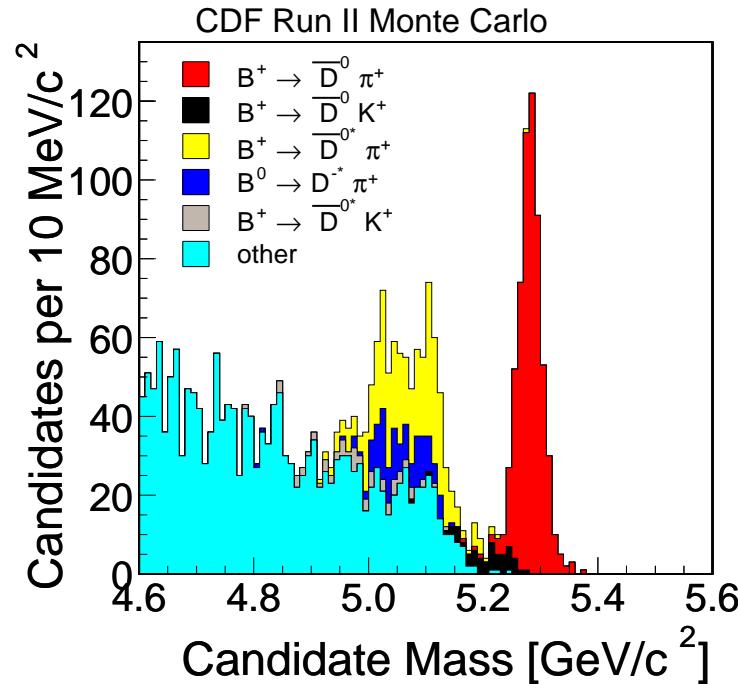
- B mass peaks are quite clean ($S/N > 2 : 1$)
- spectra have interesting structures
- use Monte Carlo to study background shapes

Background Shapes ($B^+ \rightarrow \overline{D}^0\pi^+$)



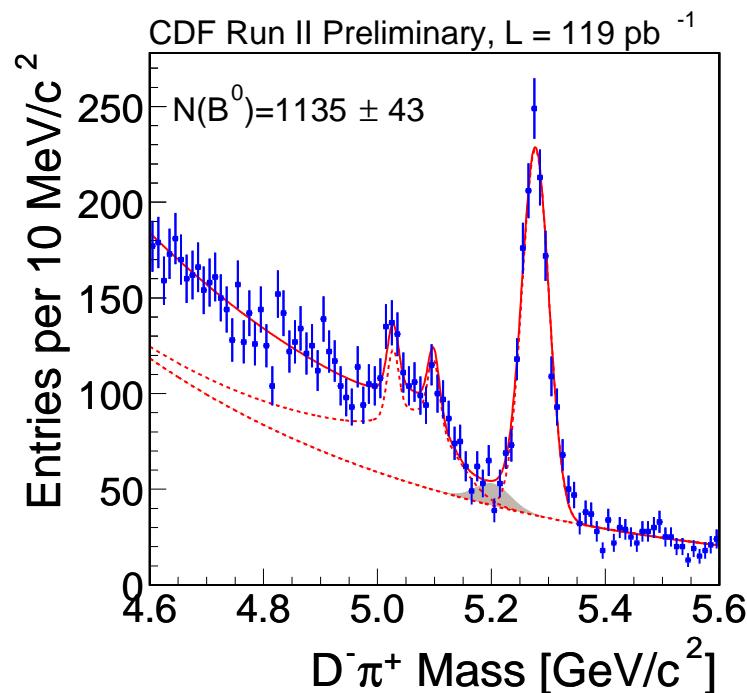
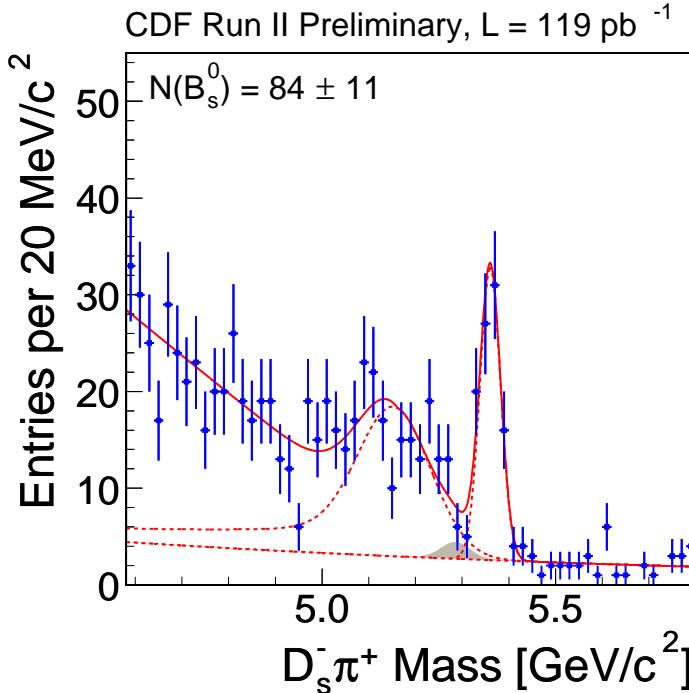
- **Monte Carlo:** $B \rightarrow \overline{D}^0 X, \overline{D}^0 \rightarrow K^+\pi^-$
- **GEANT simulation of detector and trigger**
- **spiky structures are signatures of D^* polarization**

Fitting With Templates:



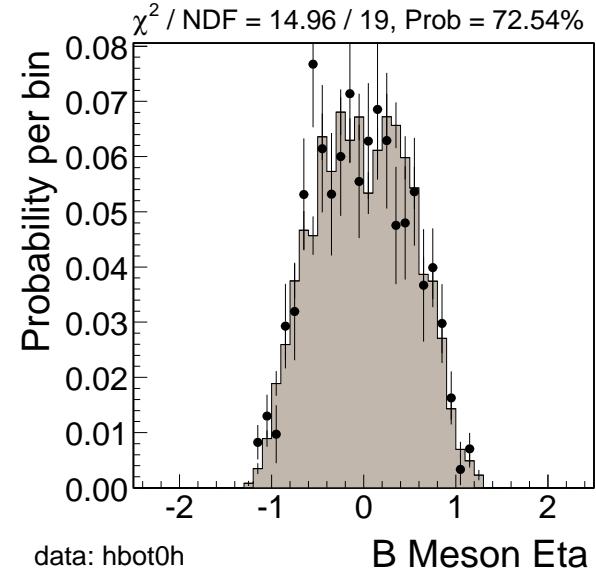
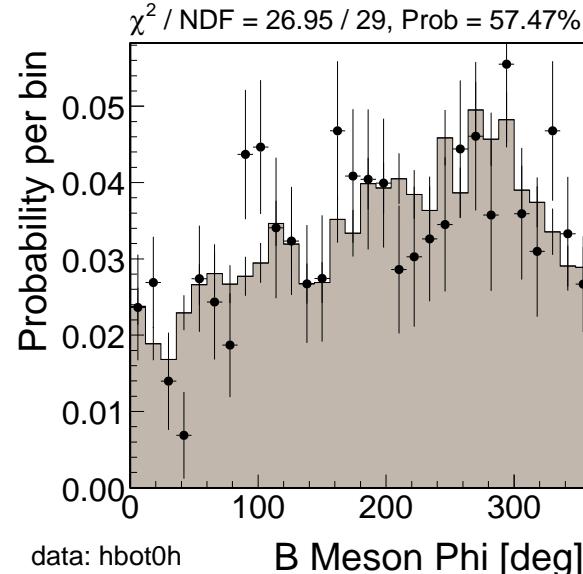
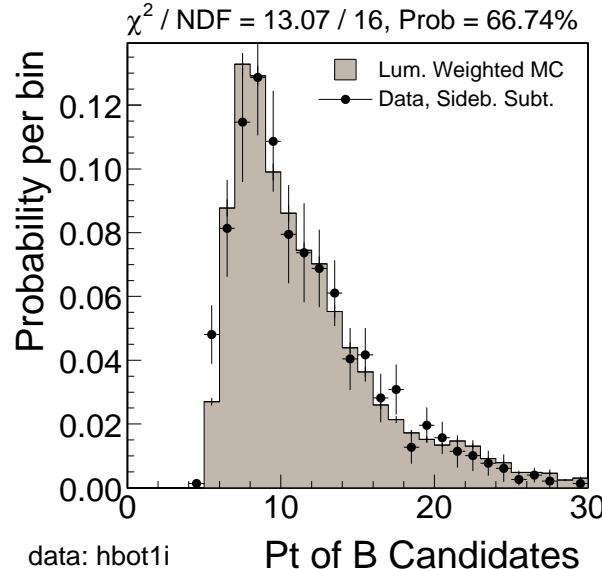
- decompose background into groups with similar features (spiky, Cabibbo suppressed, ..)
- based on Monte Carlo, create analytical templates
- extract shape parameters from MC
- keep shape parameters fixed in fit to data
- combinatorial background → single exponential

Fit Results for B_s^0 and B^0



- counting systematic error $\sim 7\%$
- $84 \pm 11(\text{stat}) \pm 4(\text{syst})$ B_s candidates
- $1135 \pm 43(\text{stat}) \pm 80(\text{syst})$ B^0 candidates
- this determines the ratio $N(B_s)/N(B_d)$
- remaining work: correct for detector effects
(different efficiencies for B_s , B^0) \Rightarrow from MC

Monte Carlo Validation



- validation done using sideband subtraction
- data/MC comparison for $B^+ \rightarrow \overline{D^0}\pi^+$
- check many other variables, find good agreement

Systematic Uncertainties:

Effect	Syst. Unc.
$B p_T$ spectrum	$\pm 1.5 \%$
XFT simulation	$\pm 0.1 \%$
ϕ^0 mass cut	$\pm 1.0 \%$
cut efficiencies	$\pm 5.0 \%$
B_s^0 lifetime	$\pm 1.4 \%$
D_s^+ lifetime	$\pm 0.3 \%$
B^0 lifetime	$\pm 0.4 \%$
D^+ lifetime	$\pm 0.04\%$
B_s^0 fitting	$\pm 5.0 \%$
B^0 fitting	$\pm 7.0 \%$
Total	$\pm 10.2 \%$

Measurement Results:

$$\frac{f_s}{f_d} \cdot \frac{Br(B_s^0 \rightarrow D_s^- \pi^+)}{Br(B^0 \rightarrow D^- \pi^+)} = 0.35 \pm 0.05(stat) \pm 0.04(syst)$$
$$= \pm 0.09(BR)$$

Using the world average value for $\frac{f_s}{f_d}$ ($\frac{f_s}{f_d} = 0.26 \pm 0.03$) we obtain:

$$\frac{Br(B_s^0 \rightarrow D_s^- \pi^+)}{Br(B^0 \rightarrow D^- \pi^+)} = 1.4 \pm 0.2(stat) \pm 0.2(syst)$$
$$= \pm 0.4(BR) \pm 0.2(PR)$$

Our measurement assumes the same fragmentation model for B_s^0 and B^0 mesons.

... now we can estimate our B_s mixing reach

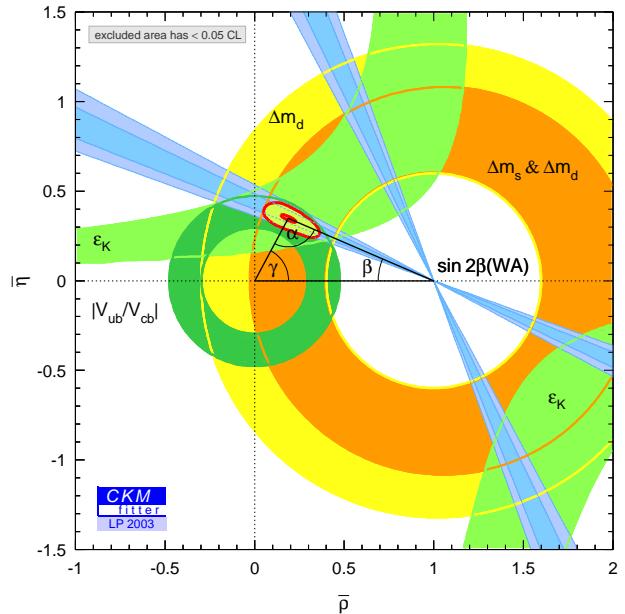
B_s^0 Mixing Reach Estimates

- Current performance:
 - $S = 1600/\text{fb}^{-1}$, $\text{S/B} = 2 : 1$
 - $\epsilon D^2 = 4\%$, $\sigma(ct) = 67 \text{ fs}$
- 2σ sensitivity
 $\Delta m_s = 15 \text{ ps}^{-1}$
with 500 pb^{-1}
-

- With “modest” improvements:
- $S = 2000/\text{fb}^{-1}$, $\text{S/B} = 2 : 1$
(improve trigger, more modes)
- $\epsilon D^2 = 4\%$, $\sigma(ct) = 50 \text{ fs}$
(event by event prim vertex, Si on beampipe)
- 3σ for $\Delta m_s = 18 \text{ ps}^{-1}$ with 1.3 fb^{-1}
- 5σ for $\Delta m_s = 18 \text{ ps}^{-1}$ with 1.7 fb^{-1}
- 5σ for $\Delta m_s = 24 \text{ ps}^{-1}$ with 3.2 fb^{-1}
- this is a difficult measurement

Conclusions

- B_s mixing at CDF II at a glance:
- initial work has begun
- reconstructed signal mode, understand rate
- work on tagging currently in progress, promising
- not a particle discovery, 3σ is relevant!
- → we want to constrain the unitary triangle
- expect to surpass world limit with 1 year of data
- beyond that, need to work on ct resolution and taggers to further extend reach
- push for more luminosity and gather more data

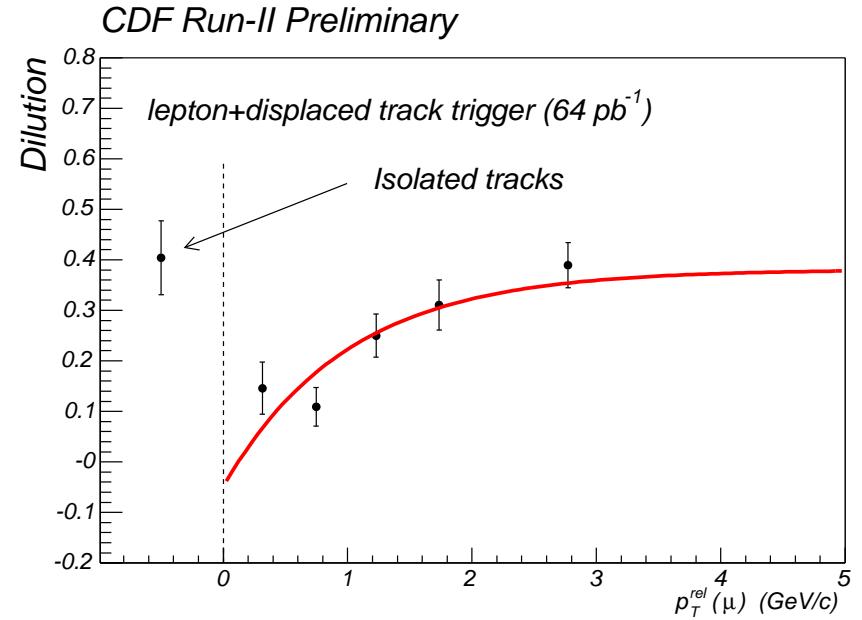
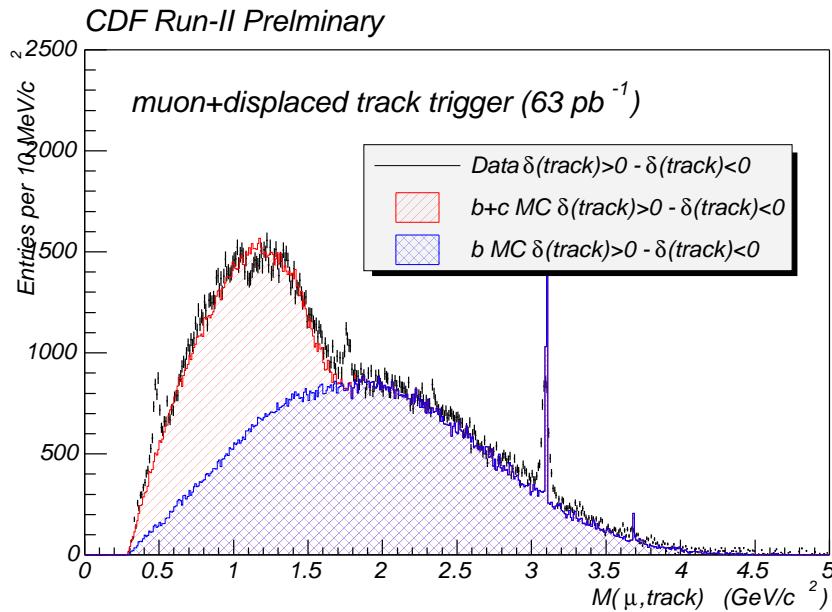


B Mixing: $p\bar{p}$ vs $\Upsilon(4S)$

Quantity	$\Upsilon(4S)$	$p\bar{p}$
Mixing B Mesons	B^0	$B^0, \textcolor{red}{B}_s^0$
$\sigma(B)$	$\sim 1 \text{ nb}$	$\sim 3 - 5 \mu\text{b}$
$\sigma(B)/\sigma(\textit{hadron})$	$\sim 1 : 4$	$\sim 1 : 1000$
ct resolution	$\sim 1.1 \text{ ps}$	$\sim 70 \text{ fs}$
tag. power (ϵD^2)	$\sim 30\%$	$\sim 5\%$

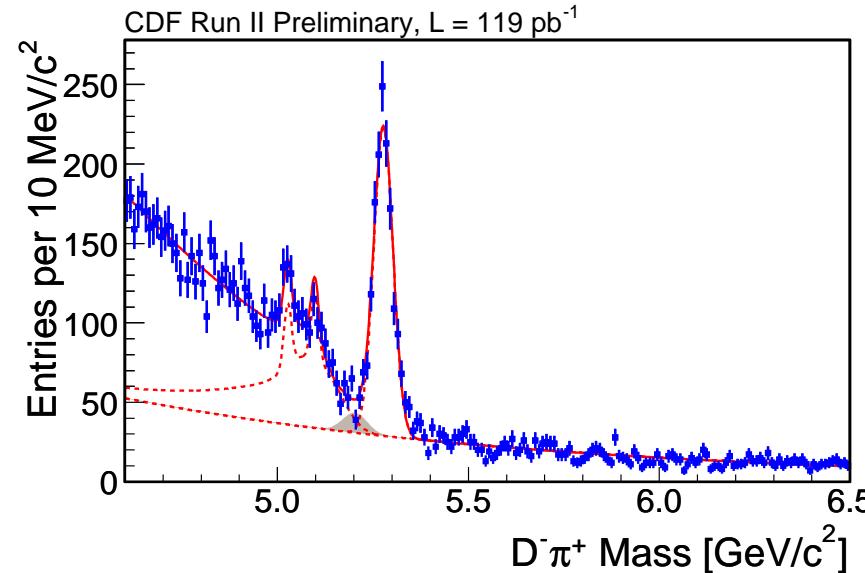
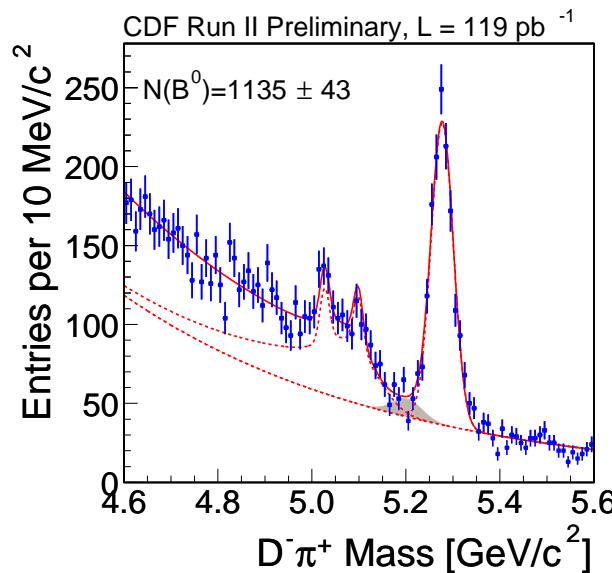
- higher B production cross section, produce B_s
- immersed in light quark background
- triggering much more important
- B's boosted in the transverse plane
- less production flavor information

Tagging Efforts in Run II



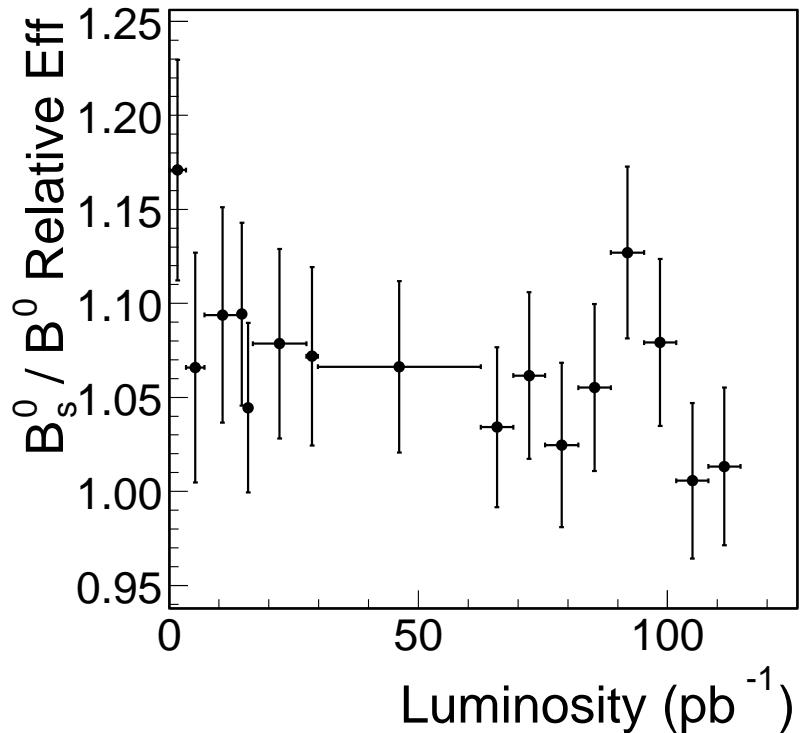
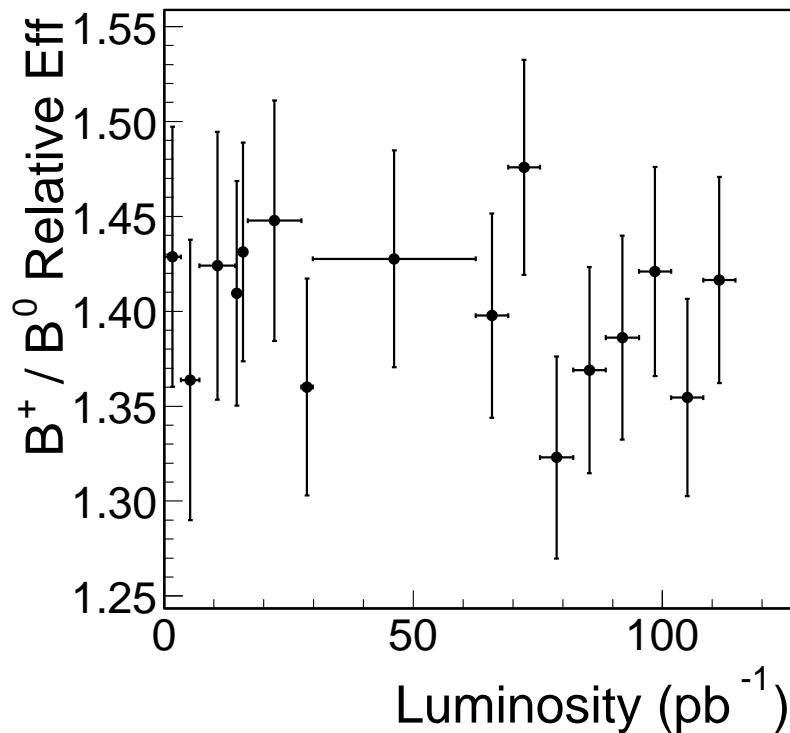
- trigger on lepton + displaced track (SVT)
- signal: l -track intersection $ct > 0$
- background: l -track intersection $ct < 0$
- require $2 \text{ GeV}/c < m(l, \text{track}) < 4 \text{ GeV}/c$
- $\sim 500\text{k}$ inclusive B decays \rightarrow test taggers
- example: measure dilution of soft muon tag

Fit Result $N(B)$ Stability



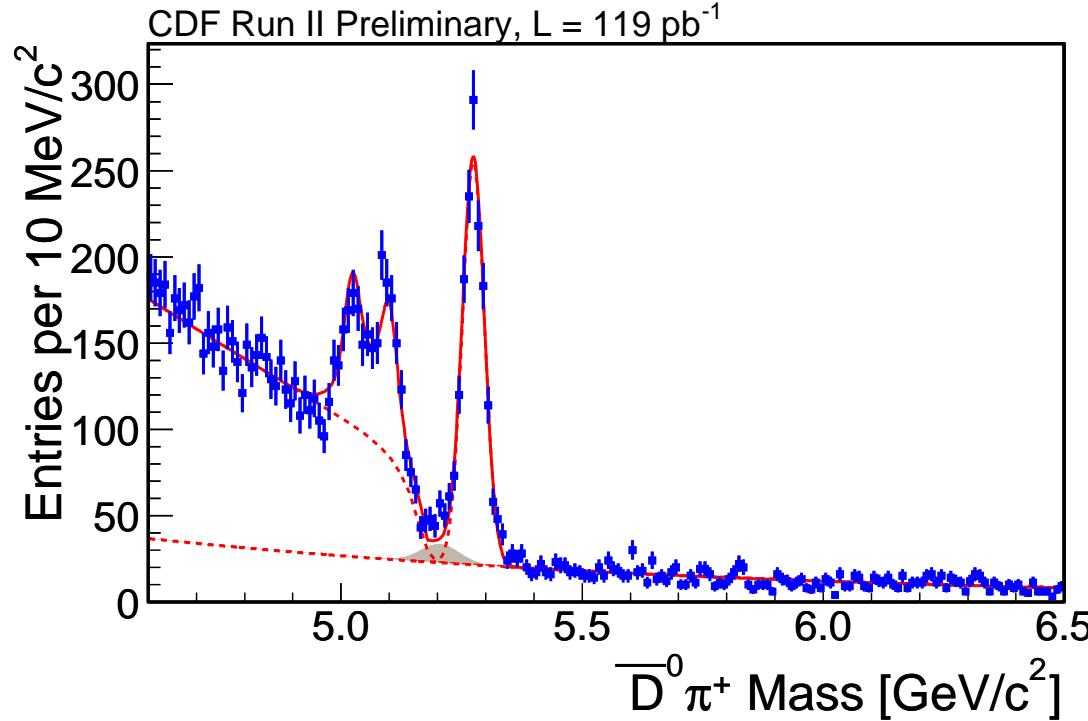
- how reliable is our counting method?
(assign counting systematic error)
- vary shape parameters for templated background
- extend fit range, fix continuum parametrization
- fits result change up to $\sim 7\%$
- can improve background parametrization

Stability of Efficiency Ratios:



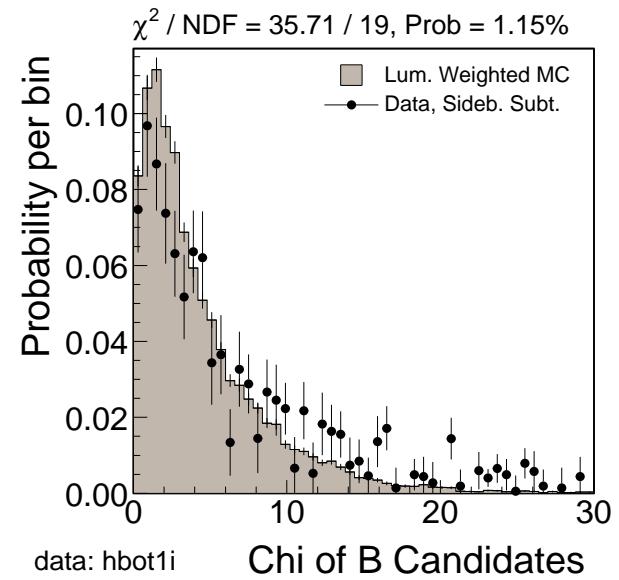
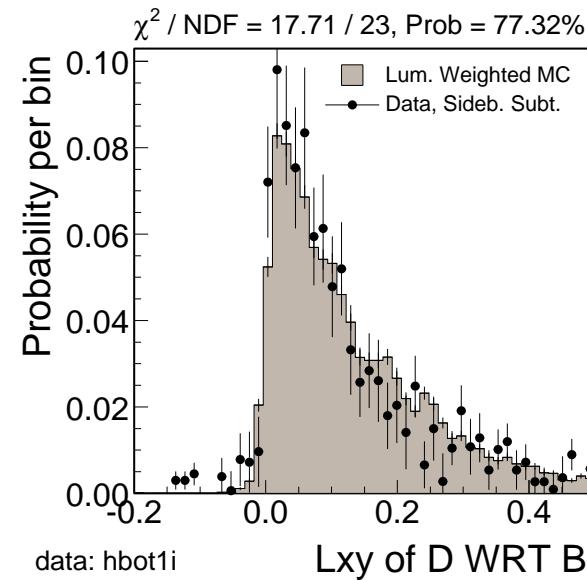
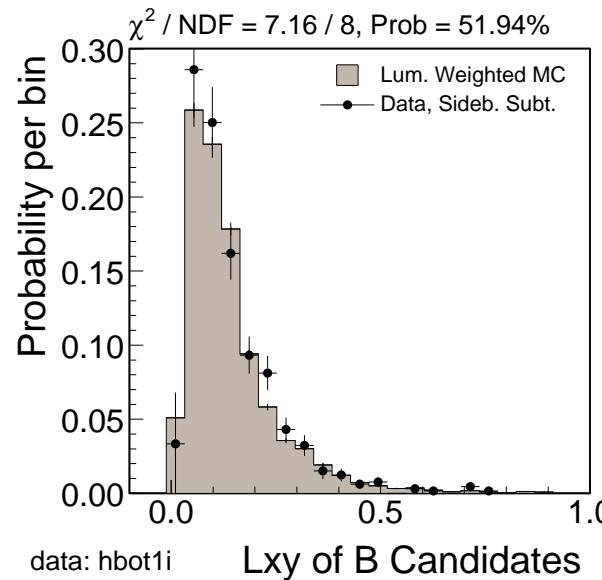
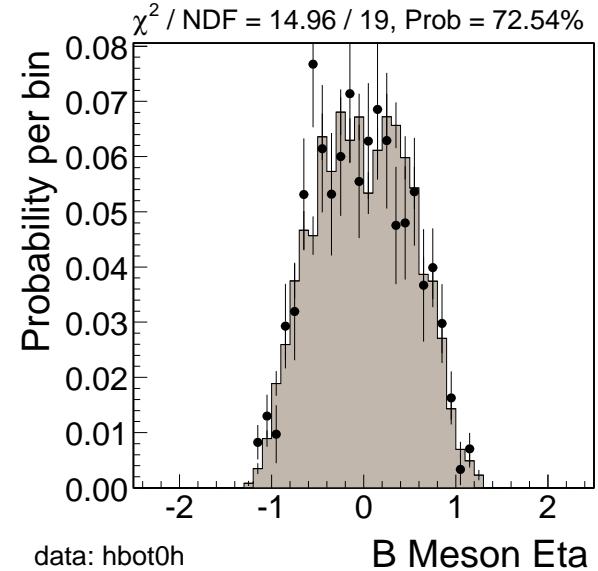
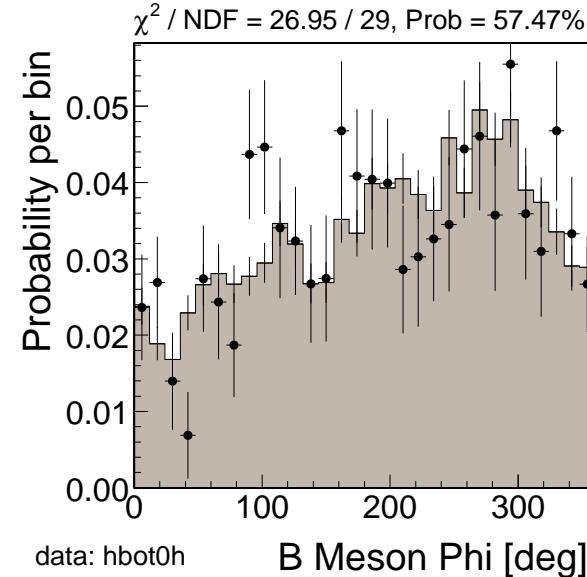
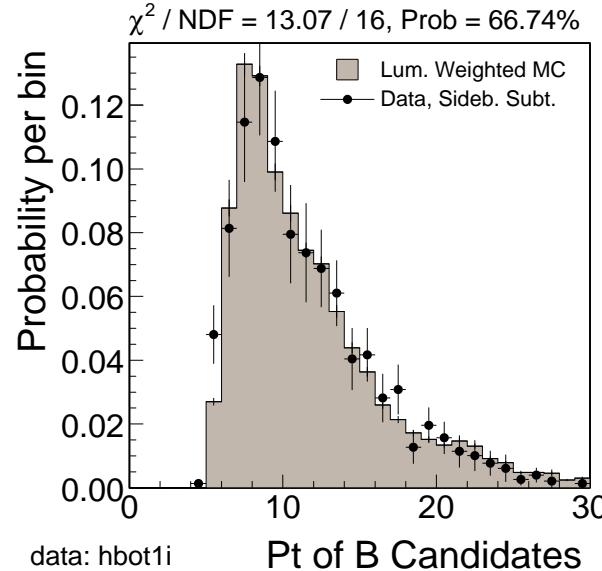
- trigger was constantly being upgraded
- concern: this may affect the efficiencies
- the ratio of total efficiencies is stable regardless of trigger efficiency change
- measurement quite robust to trigger conditions

Monte Carlo Validation Method



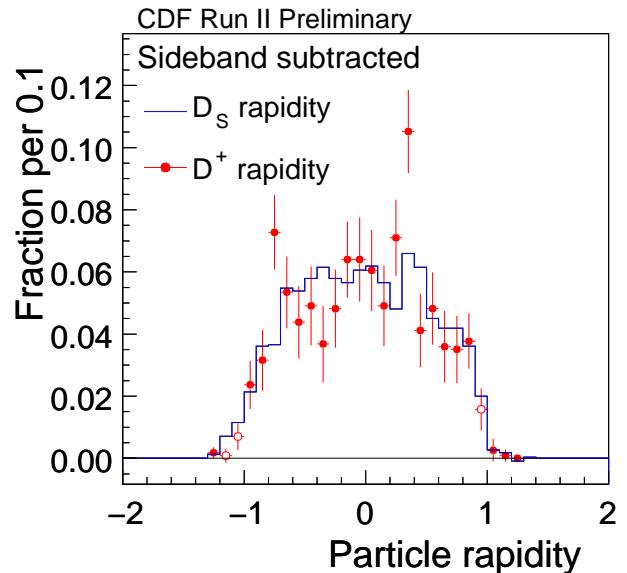
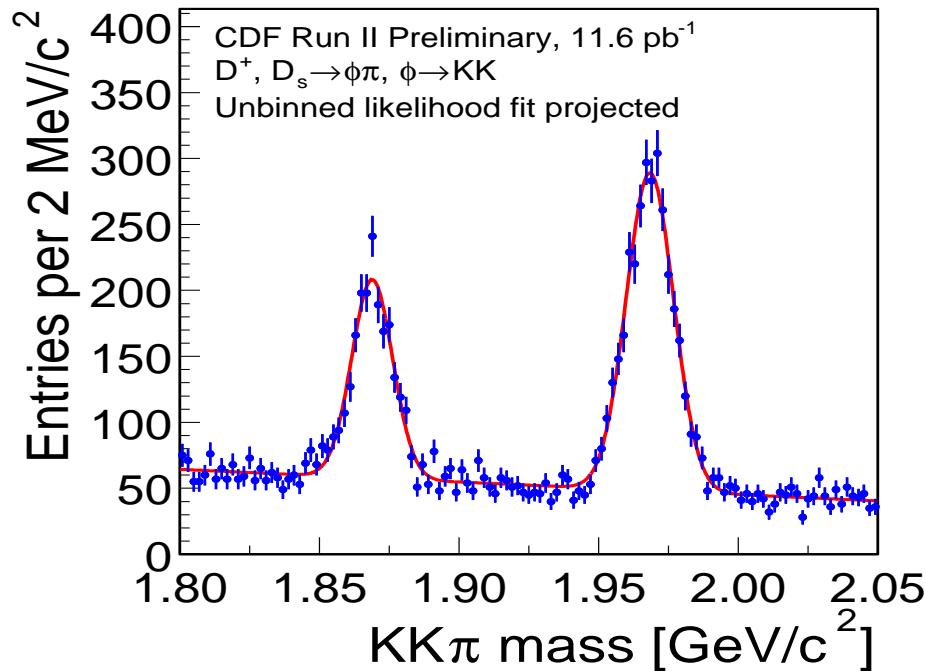
- high and low-mass sideband: different composition
- subtract only high-mass sideband
- but scale up number of events
(using the exponential fit for the comb. background)
- check relevant distributions for both B^0 and B^+
- in addition, check N-1 cut efficiencies

Monte Carlo Validation

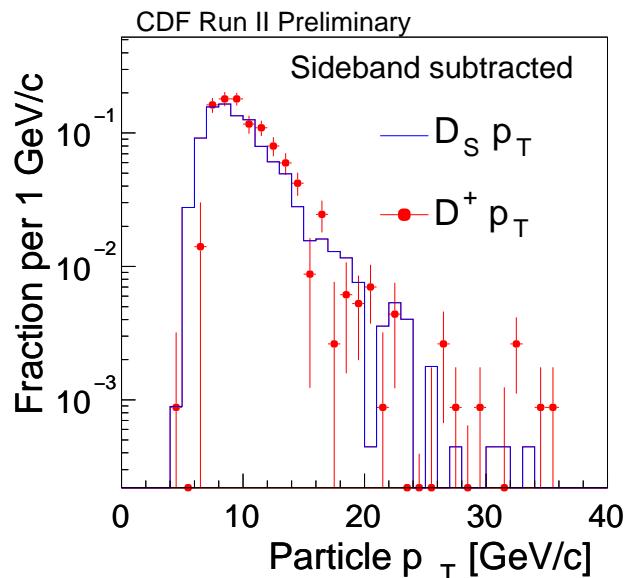


- check many variables, good agreement for most

D Meson Mass Difference



- 1.4k D^+ , 2.4k $D_s^+ \rightarrow \phi\pi^+$
- **mass resolution** $\sim 8 \text{ MeV}/c^2$
- **similar kinematics**
- **expect small syst. errors**



Mass Difference Result

$$m(D_s^+) - m(D^+) = 99.41 \pm 0.38(\text{stat}) \pm 0.21(\text{syst}) \text{ MeV}/c^2$$

PRD 68 (2003) 072004 - First Tevatron Run II publication

systematics small, dominated by bkg model:

Effect	Syst.[MeV/c ²]
fitting	0.14
event selection	0.11
momentum scale	0.10
tracker effects	0.06
calibration procedure	0.03
Total	0.21

- PDG '02: $99.2 \pm 0.5 \text{ MeV}/c^2$
- CLEO2 (1998): $99.5 \pm 0.6 \pm 0.3 \text{ MeV}/c^2$
- BaBar (2002): $98.4 \pm 0.1 \pm 0.3 \text{ MeV}/c^2$